Future Multi - Megawatt Proton Facilities

Presented at ICFA HB-2004

Introduction

Issues of high intensity beam acceleration

Proposals and Designs of Future Facilities with Multi - Megawatt Beam Power

BROOKHAVEN NATIONAL LABORATORY

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C-AD seminar
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High proton beam power applications

$$P = E \times I_{ave} = E \times I_{peak} \times DF$$

Kinetic energy (E) and Duty Factor (DF) depend on application:

Nuclear waste transmutation and accelerator driven sub-critical reactors:

- CW or high DF to minimize mechanical shock
- E: 1 – 10 GeV (minimize power deposition in window, fully absorb beam in reactor)

Production of intense secondary beams:

- Neutrons: DF: CW - 10^{-4}, E: 0.5 - 10 GeV (neutron production ~ prop. to beam power)
- Kaons: DF ~ 0.5 (minimize pile-up in detector), E: > 20 GeV
- Neutrino super-beam: DF: ~ 10^{-5}(suppress background), E: > 1 GeV (depends on neutrino beam requirements)
- Muons for neutrino factory: DF: ~ 10^{-5} (pulsed cooling channel), E: > 10 GeV (for 5MW, I_{peak} > 50A)
- Muons for muon collider: DF: ~ 10^{-7} (maximize luminosity), E: ~ 20 – 30 GeV (for 5MW, I_{peak} = 1.7 – 2.5 kA)

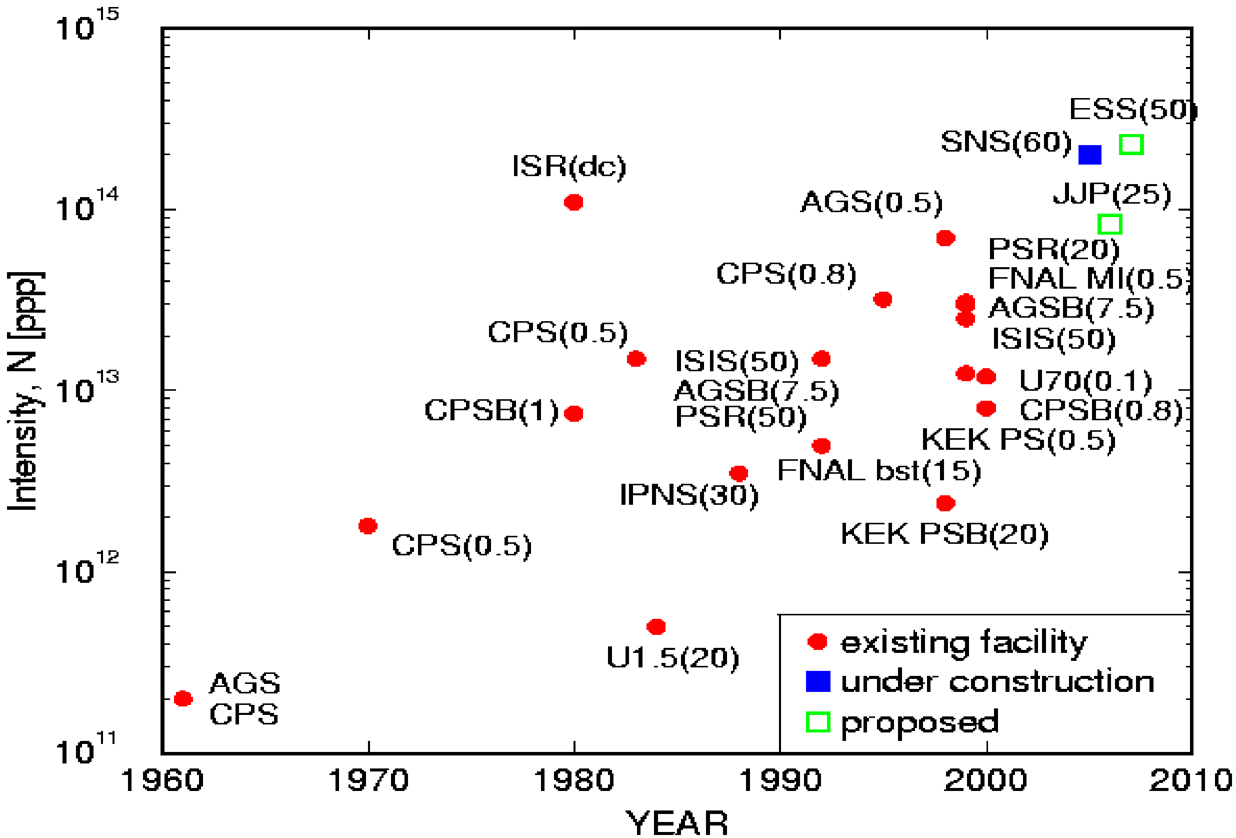
Main challenges for future Multi-MW facilities

- Beam loss
  - Maintainability requires losses ~ 1 W/m
  - For 1 km/10MW facility: total losses of 1 kW or 10^{-4} at top energy
  - Since losses are not evenly distributed lower values may be required at some locations

- Power consumption efficiency
  - Efficiency = (beam power)/(wall plug AC power)
  - Present facilities have typically low efficiency (AGS: ~ 1 %)
  - Need new technologies for efficient beam power production

- High power production targets

Intensity history of multi-GeV proton machines



Exp. Growth (similar to max. energy history)

BNL AGS and CERN PS still leading after more than 40 years!

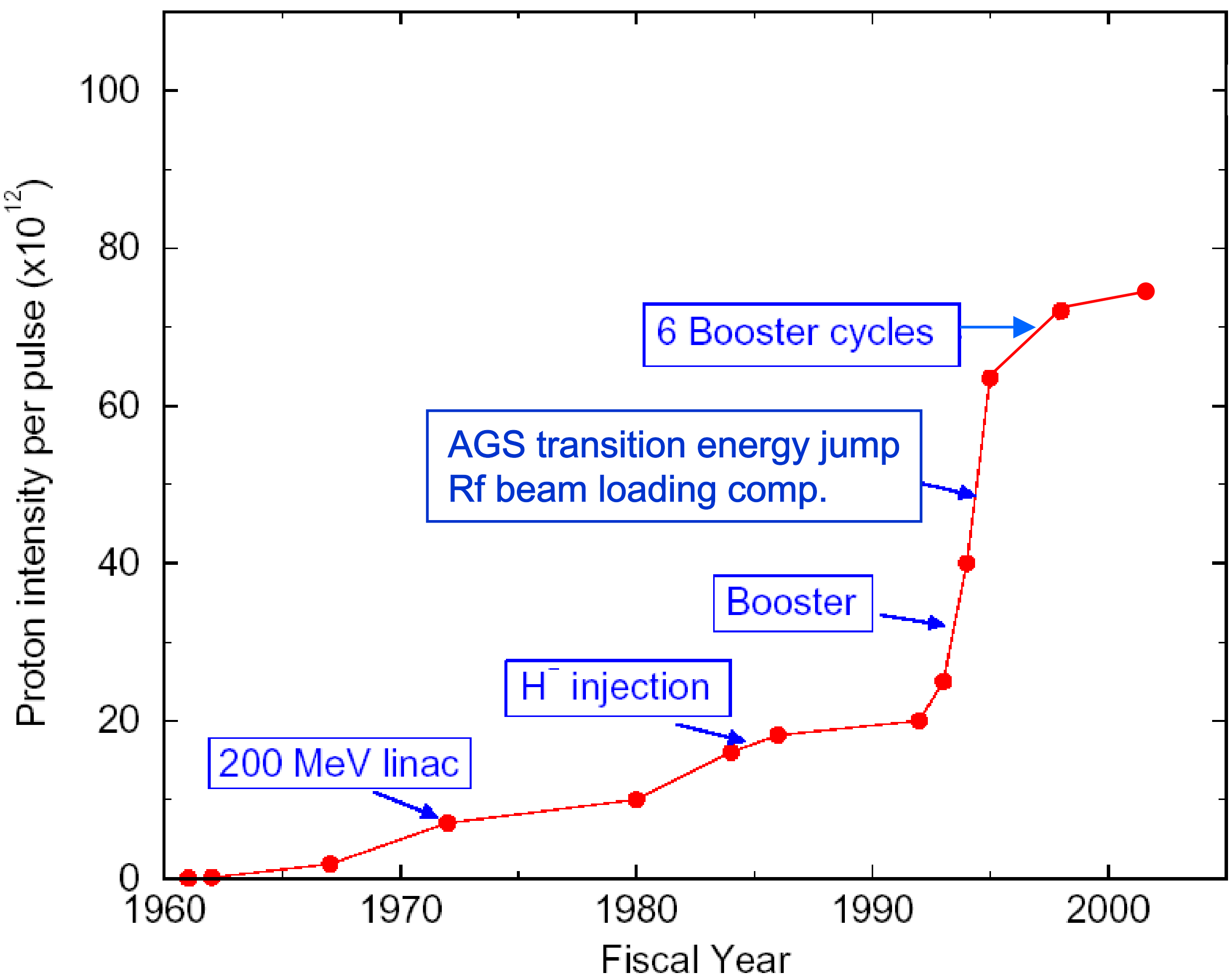
Progress in high intensity beam acceleration

Technologies developed for high intensity beams:

- Low loss charge exchange injection (PSR, SNS, …
- Boosters (CERN, FNAL, BNL, KEK, …
- Rapid cycling synchrotron (FNAL, ISIS, …
- (CW) RFQs (LEDA,…
- Super-conducting rf (SNS, …
- Transition energy jump or avoidance (CERN, AGS, J-Parc, …
- RF beam loading compensation (AGS, …
- Electron cloud cures (LANL PSR,…

Need both machines and simulations to make progress!

AGS Intensity History



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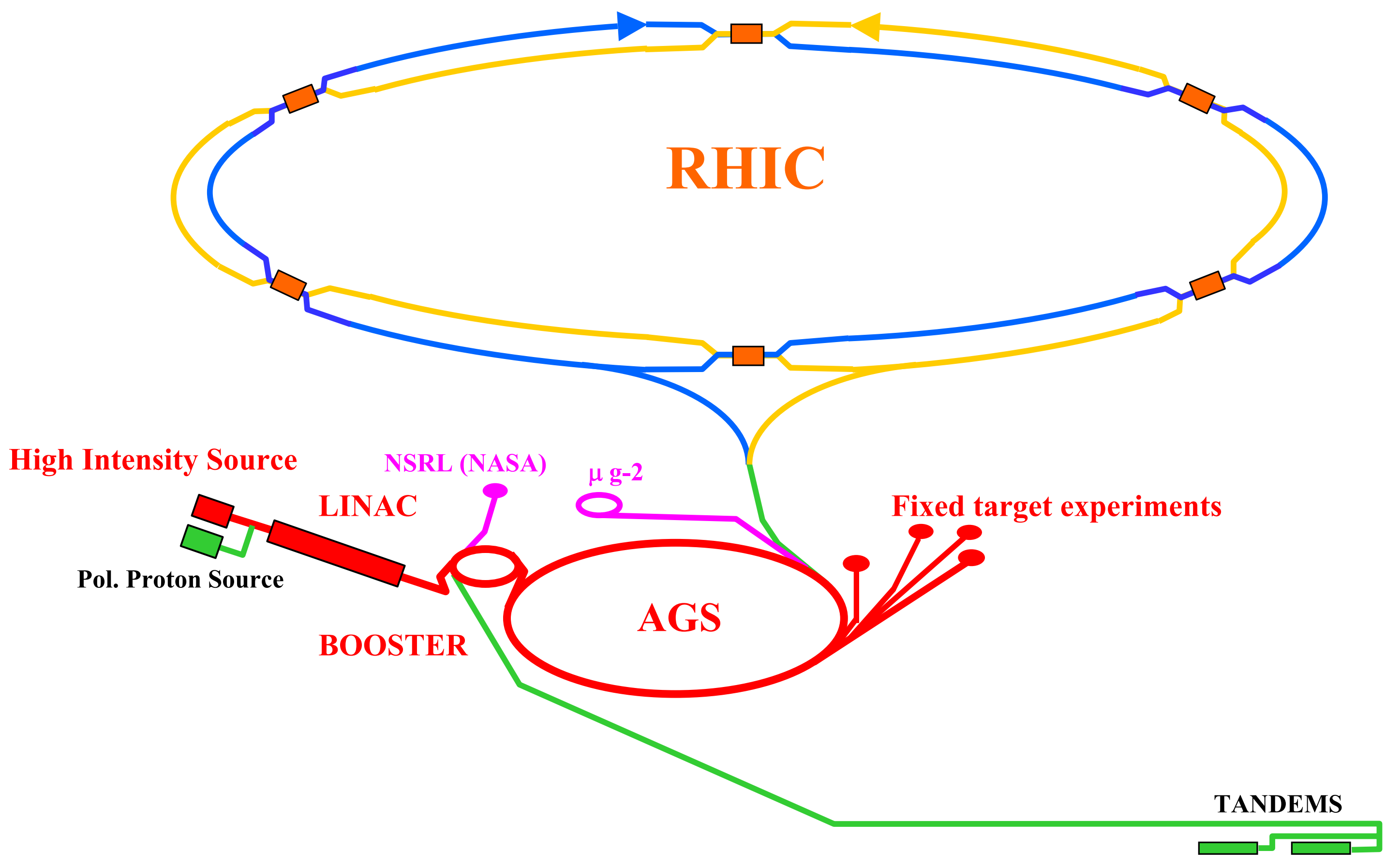
AGS/RHIC Accelerator Complex



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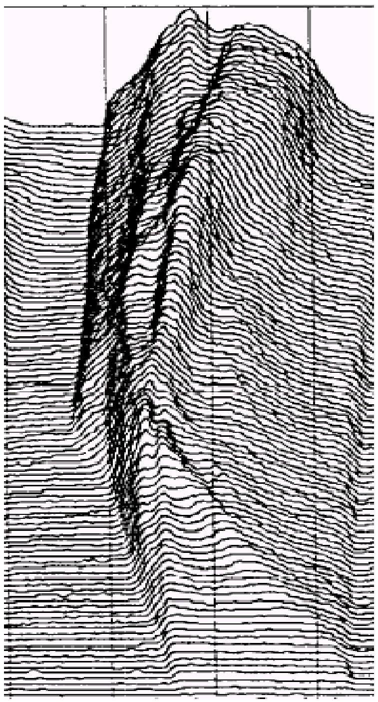
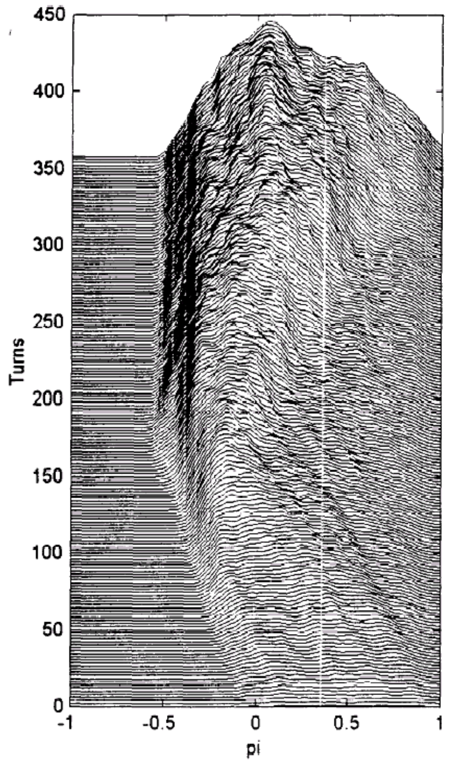
H^- injection into the Booster

Measurement



Simulation



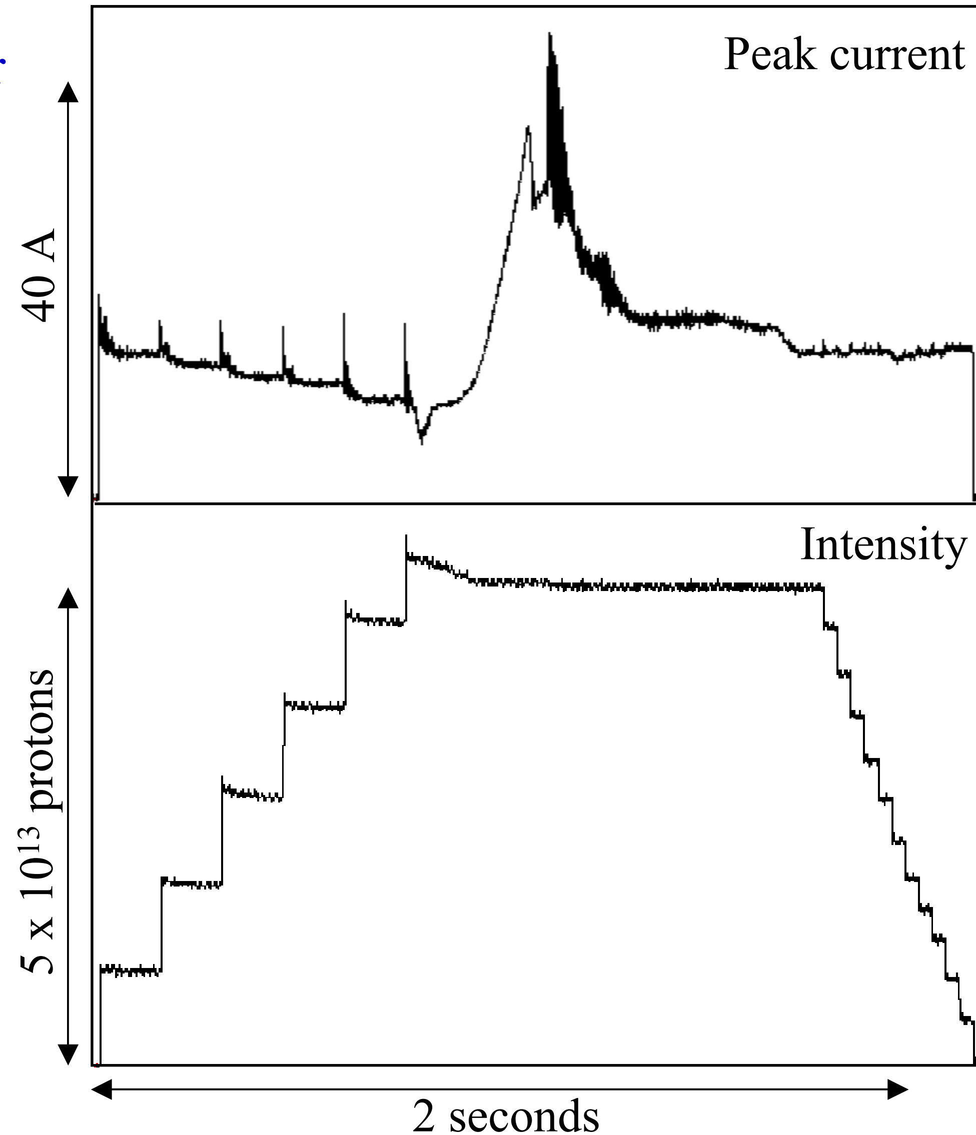
Injected:
23×10^{12} ppb
1.3 eVs

Circulating:
17×10^{12} ppb
3.0 eVs

- 90 mA H^- magnetron source, potential for DF upgrade (now 0.5 %)
- High B dot gives effective longitudinal phase space painting.
- Injection period is approx. equal to synchrotron period.

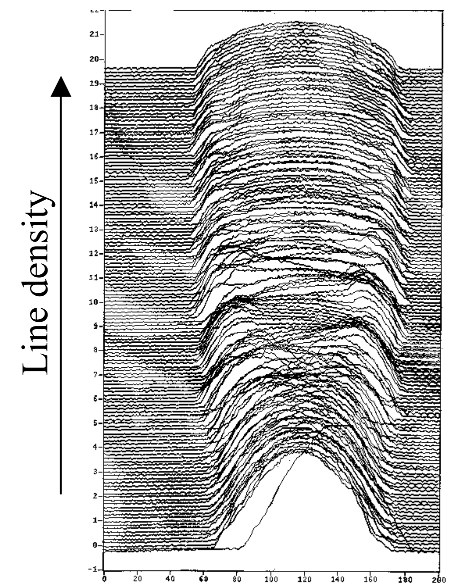
AGS High Intensity Performance

- 6 single bunch transfers from Booster
- Peak intensity reached: 72×10^{12} ppp
- Bunch area: 3 eVs at injection
  10 eVs at extraction
- Intensity for FEB ops: 60×10^{12} ppp
- Strong space charge effects during accumulation in AGS
- 2nd order transition energy jump limits available momentum aperture.
- Chromatic mismatch at transition causes emittance dilution



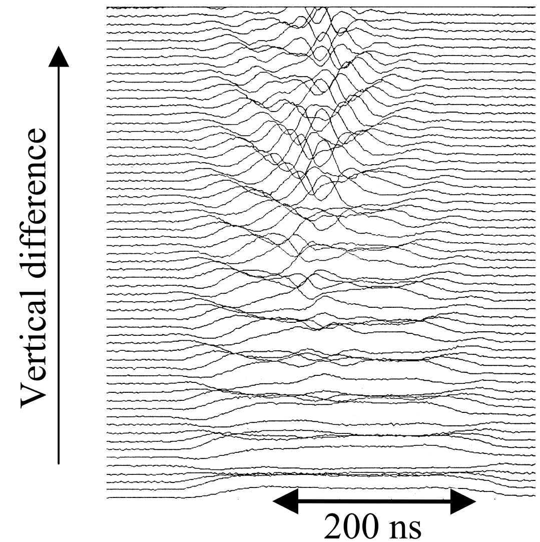
High intensity bunch-to-bucket transfer

- Incoherent tune spread ~ 0.1 → significant effects during beam accumulation
  Expected for incoherent tune spread of 0.3 at
  Booster injection: tune spread ~ $C/\beta\gamma^2$ ~ $1/\gamma$



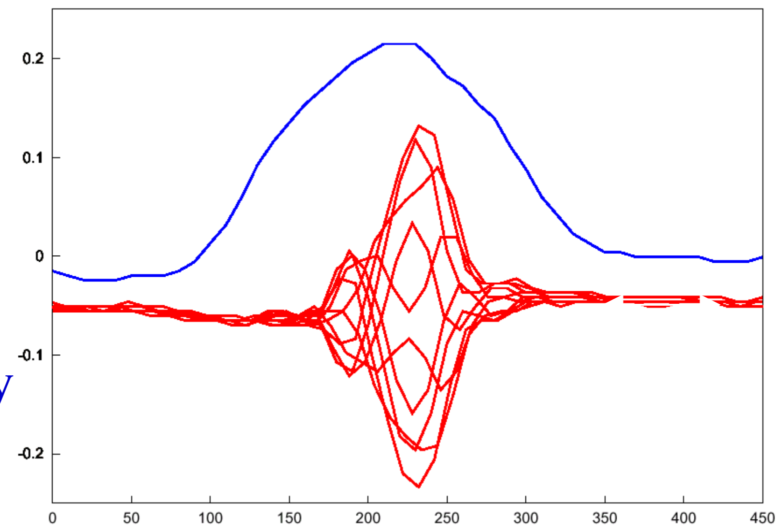
- Longitudinal emittance dilution at AGS injection through mismatch followed by smoothing with high frequency (93 MHz) cavity.
- Needed to avoid excessive space charge tune spread and coupled bunch instabilities.

- For 13 × 10^{12} ppb: coherent space charge tune shift varies along bunch: 0 → ~ 0.1 at bunch center
- Dipole mismatch difficult to damp
- Quadrupole mismatch can cause halo

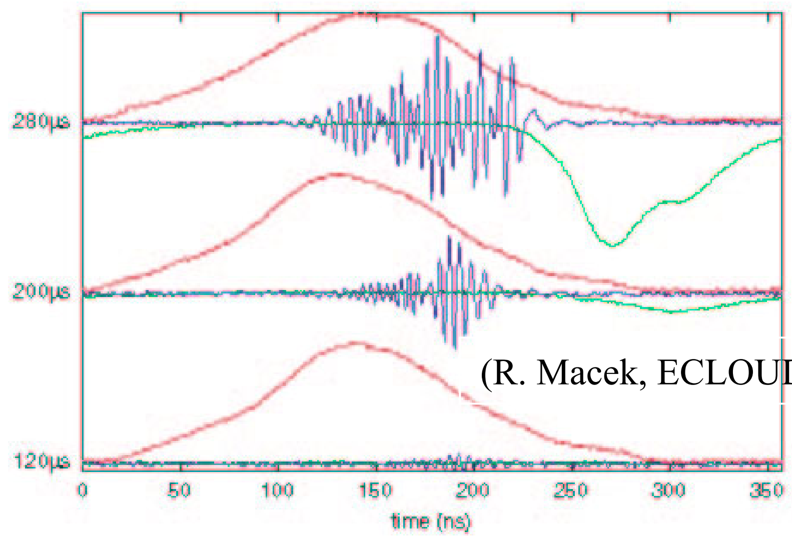


Single bunch transverse instabilities

- AGS Injection (1.9 GeV)
- 12×10^{12} ppb, ~ 3 eVs
- Single bunch
- Transverse pick-up bandwidth limited
- Cured with non-zero chromaticity



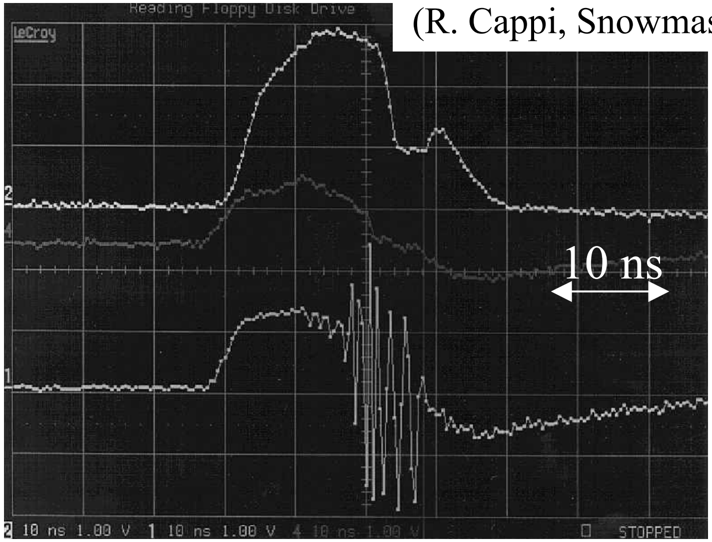
- LANL PSR (0.8 GeV)
- 50×10^{12} ppb
- Occurs with low rf voltage
- Cured with high rf voltage



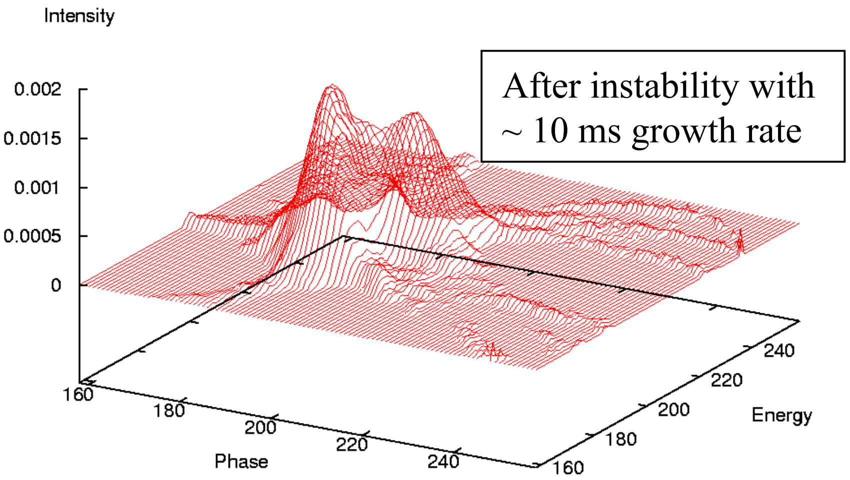
(R. Macek, ECLOUD 2004)

Single bunch transverse instabilities (2)

- CERN PS transition (~ 7 GeV)
- 7×10^{12} ppb, > 2.2 eVs
- Occurs close to transition
- Cured with long. blow-up and non-zero chromaticity

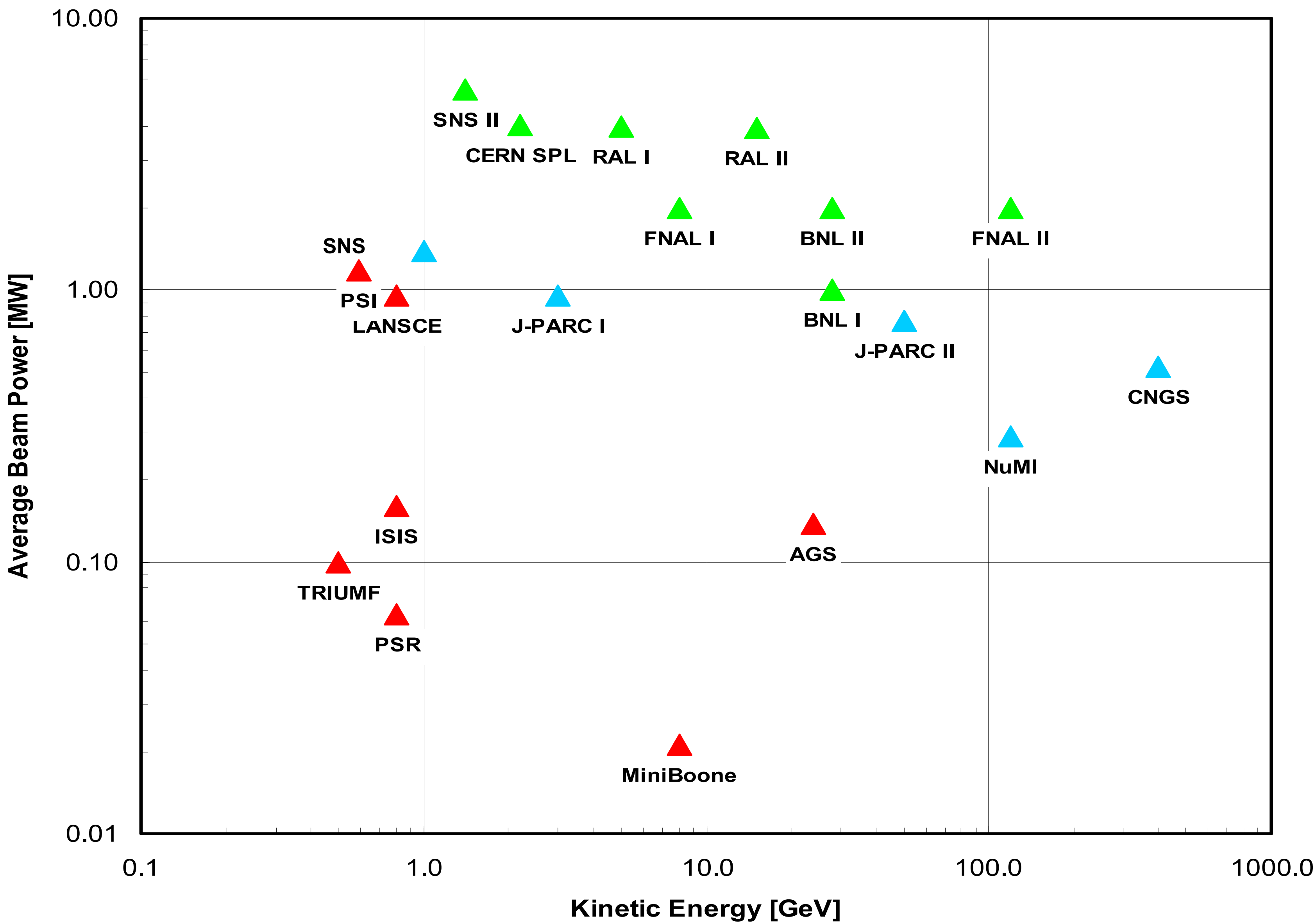


- RHIC transition (~ 20 GeV/n)
- 7×10^{10} cpb, ~ 0.3 eVs/n
- Occurs close to transition
- Cured with octupoles and non-zero chromaticity



E-cloud and/or broadband impedance

High Beam Power Proton Machines



Design options for high power facilities

	design:	issues/challenges:
CW or high DF:	Cyclotron + p source	$E \leq 1$ GeV
	SC Linac + p source	CW front end (RFQ, DTL)
Low DF:	Linac + accum. ring	$E \leq 5$ (8?) GeV (H^- stripping)
	Linac + RCS	Rep. rate < 100 Hz, $P_{RSC}/P_{Linac} \leq 10$
	Linac + FFAG	Rep. rate $\leq$ 1 kHz, $P_{RSC}/P_{FFAG} \leq 3$
	Linac + n $\times$ RCS	For high energy
		Bunch-to-bucket transfers
		High gradient, low frequency rf

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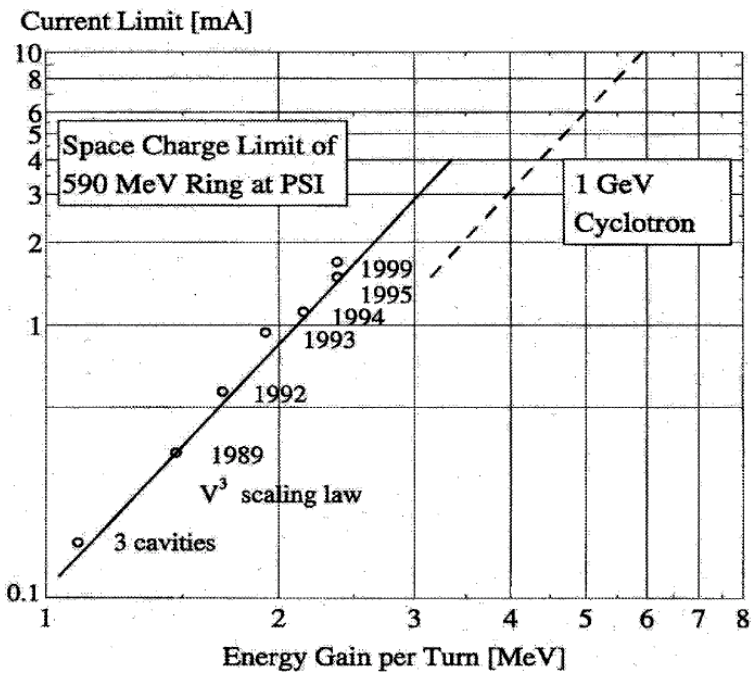
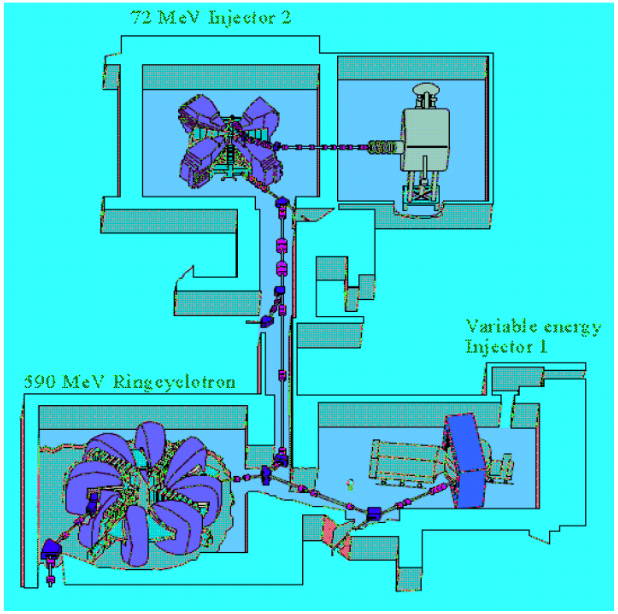
PSI SINQ Cyclotron Facility

Achieved: 590 MeV, 2 mA, 1.2 MW

Upgrade: 590 MeV, 3 mA, 1.8 MW

Possible: 1000 MeV, 10 mA, 10 MW





Space charge current limit scales with third power of rf voltage.

CW Super-conducting Linac

Several proposals, but no existing facility

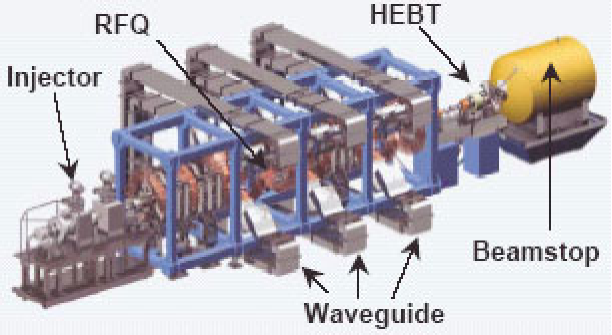
Issues: CW front end (RFQ, DTL), operating efficiency of SC cavities/rf system

Low Energy Demonstration Accelerator (LEDA):

6.7 MeV, 100 mA CW (0.7 MW)

Successful demonstration of CW front-end

Bench-marking of halo simulation codes



High Intensity Proton Injector (IPHI, CEA)

3.0 MeV, 100 mA CW (0.3 MW)

First beam in 2006, to be used for SPL (CERN)

International Fusion Materials Irradiation Facility (IFMIF):

2 x 125 mA D^+, 5 MeV (RFQ), 40 MeV (DTL) (2 x 0.6 MW, 2 x 5 MW)

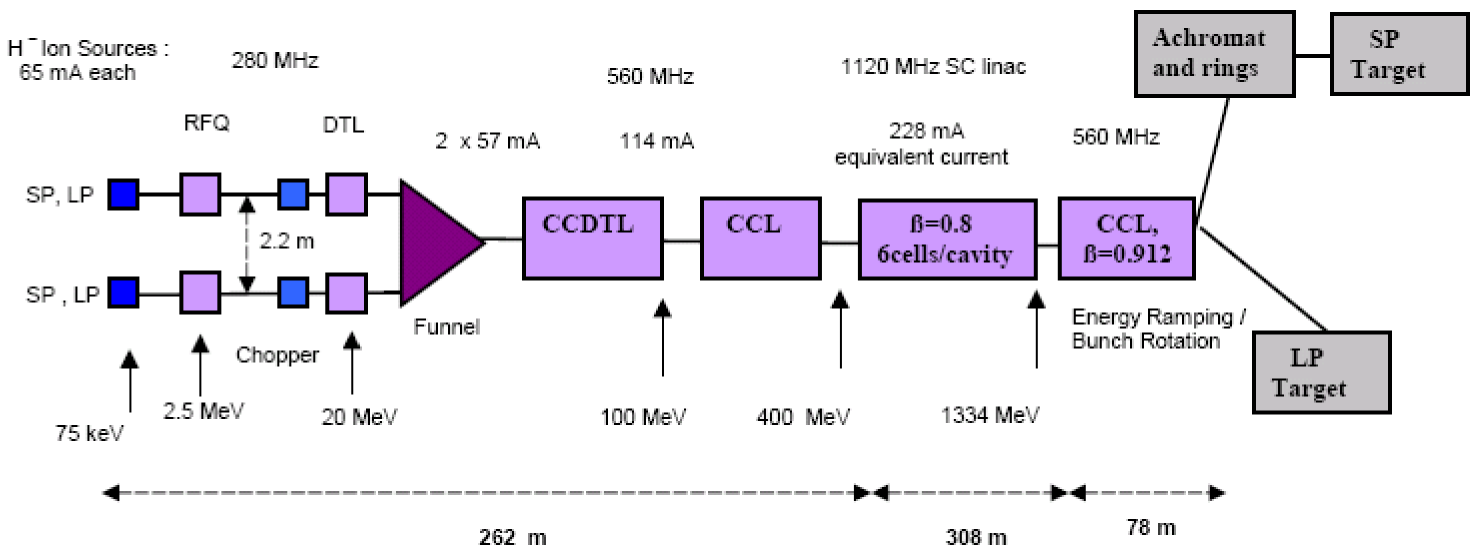
Start 2009 (?)

CW Super-conducting Linac (2)

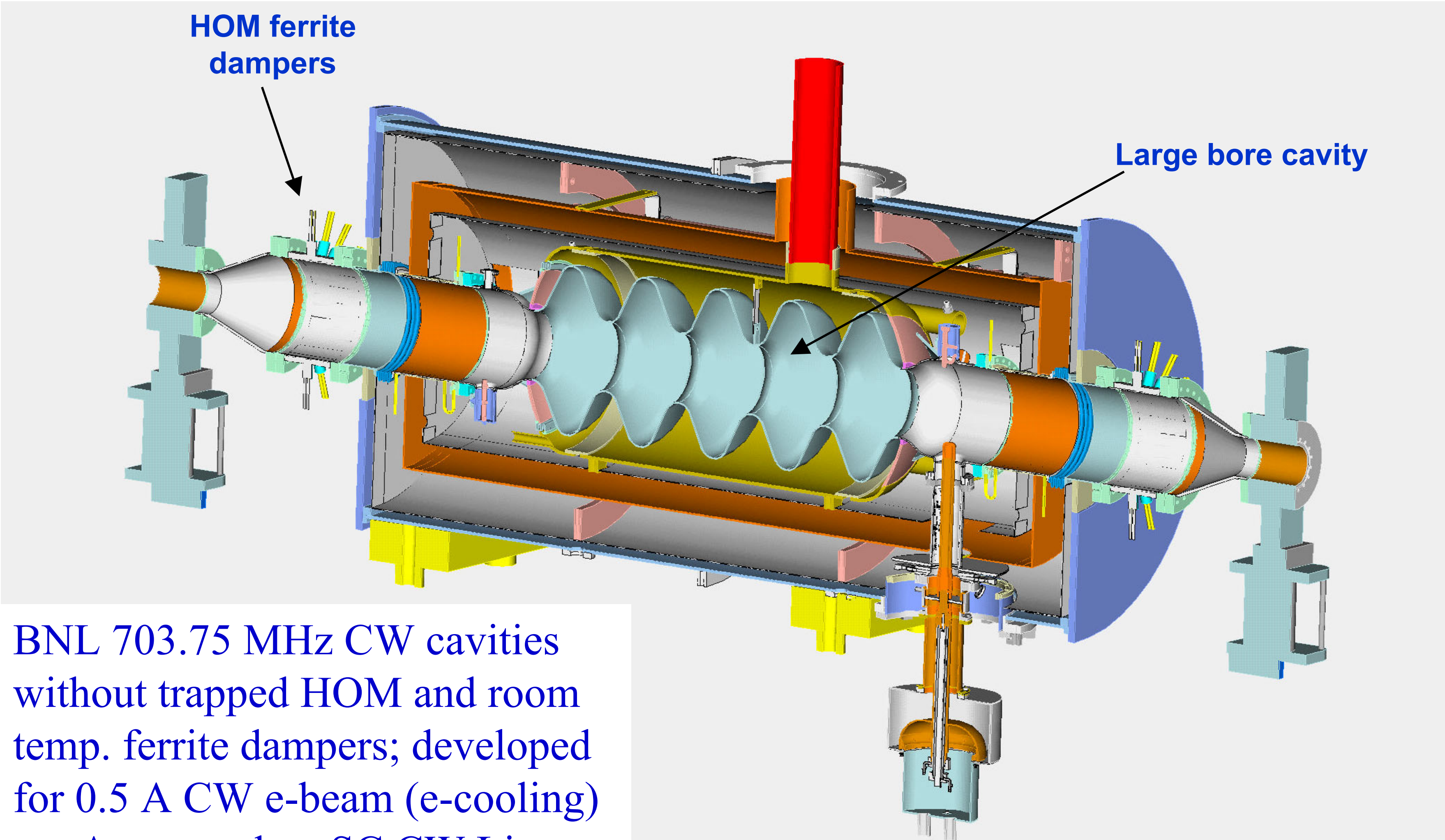
Super-conducting Linac designs: APT Linac, ESS (Long Pulse)

ESS – Long Pulse Reference Design: 1334 MeV, 3.7 mA (3.3% DF), 5 MW

Beam / AC power (LP): 24% (NC 19%, SC 28%)



703.8 MHz CW Superconducting Cavity for High Intensity Beams



BNL 703.75 MHz CW cavities without trapped HOM and room temp. ferrite dampers; developed for 0.5 A CW e-beam (e-cooling) → Ampere-class SC CW Linac

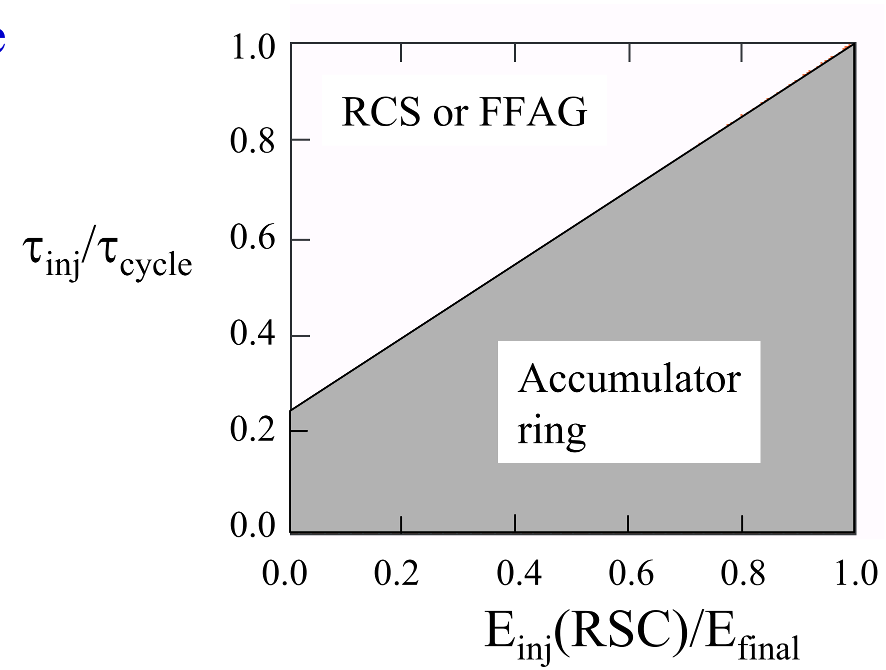
Low Duty Factor Facilities – Accumulator vs. RCS/FFAG

Linac + accum. ring	$E \leq 5$ (8?) GeV (H^- stripping)
Linac + RCS	Rep. rate < 100 Hz, $P_{RCS}/P_{Linac} \leq 10$
Linac + FFAG	Rep. rate ≤ 1 kHz, $P_{FFAG}/P_{Linac} \leq 3$

Maximum beam power if cost scales with total length (linac + ring):

For 1 ms linac pulse length and $E_{final} \sim 5$ GeV

→ Accumulator ring is more cost effective
unless rep. rate > 200 Hz (→ FFAG)



CERN Superconducting Proton Linac Proposal

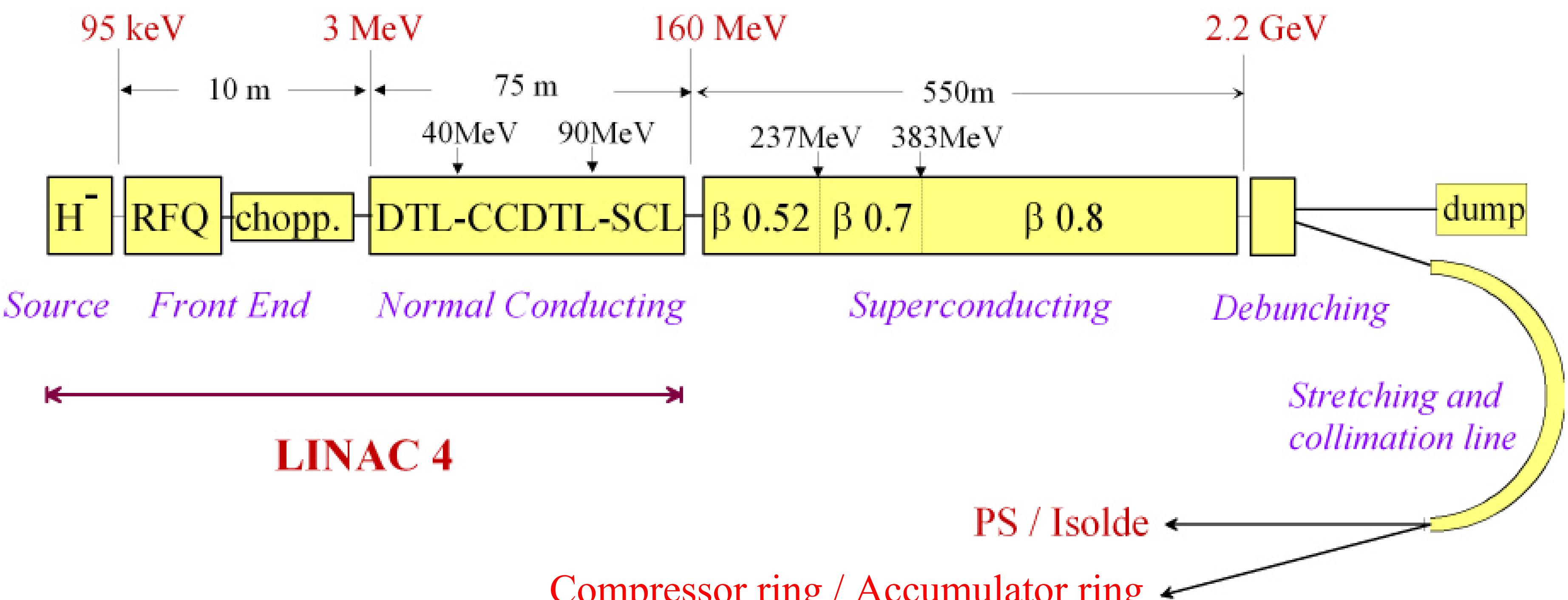
2.2 GeV, 1.8 mA , 4 MW, 50 Hz

After Linac: DF: 8.2 %, I_{peak} = 22 mA (H^-)

After accumulator: DF: ~ 10^{-4}, I_{peak} ~ 18 A

After compressor: DF: ~ 2 x 10^{-5}, I_{peak} ~ 90 A

Solid Nb super-conducting 704 MHz cavities



FNAL SCL Proton Driver Proposal

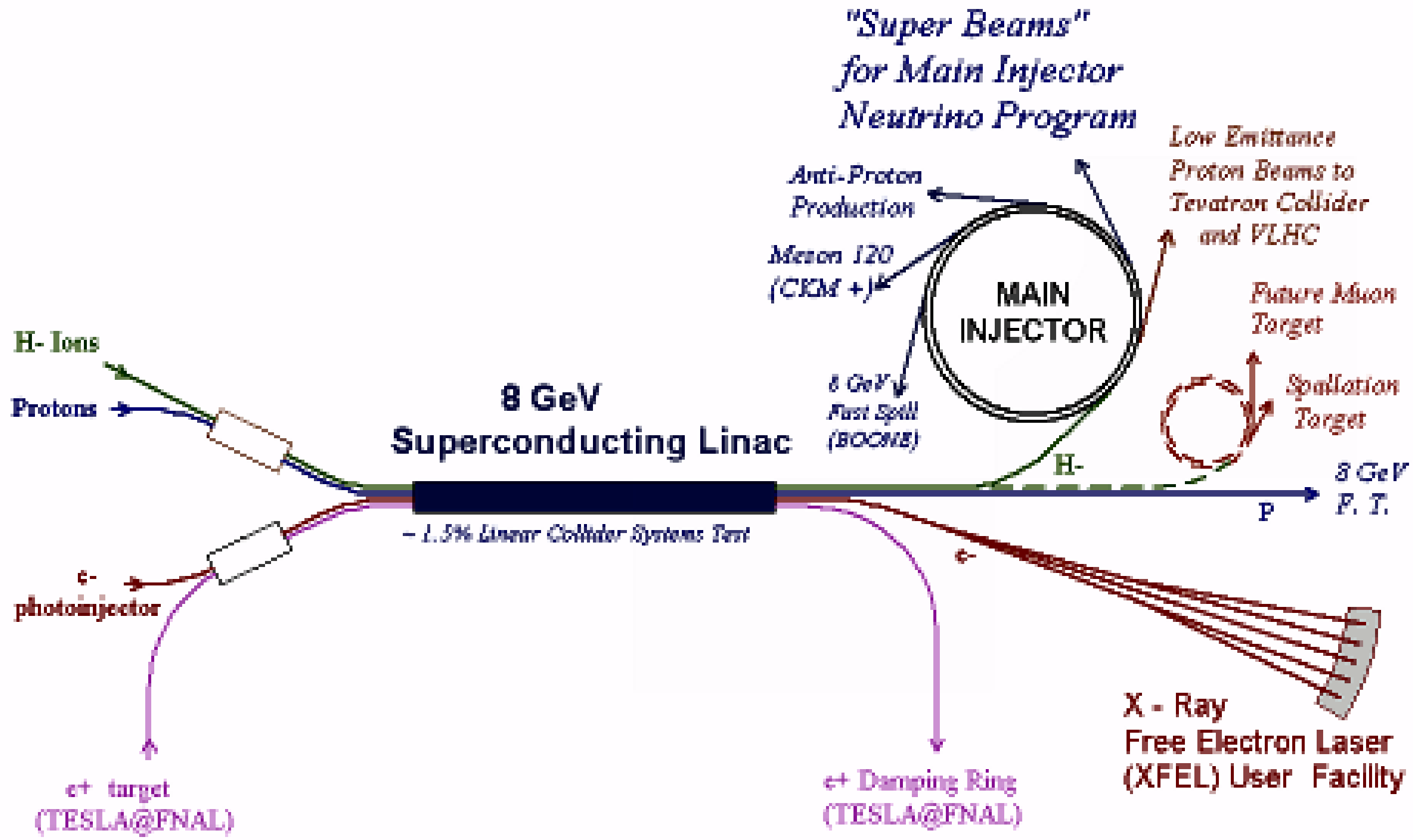
Super-conducting linac: 8.0 GeV, 0.25 mA , 2 MW, 10 Hz

After Linac: DF: 0.9 %, I_{peak} = 28 mA (H^-)

After MI (accumulator): DF: ~ 6 x 10^{-5}, I_{peak} ~ 5 A

After MI (acceleration): 120 GeV, 2 MW, 0.7 Hz, DF: ~ 4 x 10^{-6}, I_{peak} ~ 5 A

1.3 GHz Tesla cavities, stripping of H^- (all fields < 600 G)



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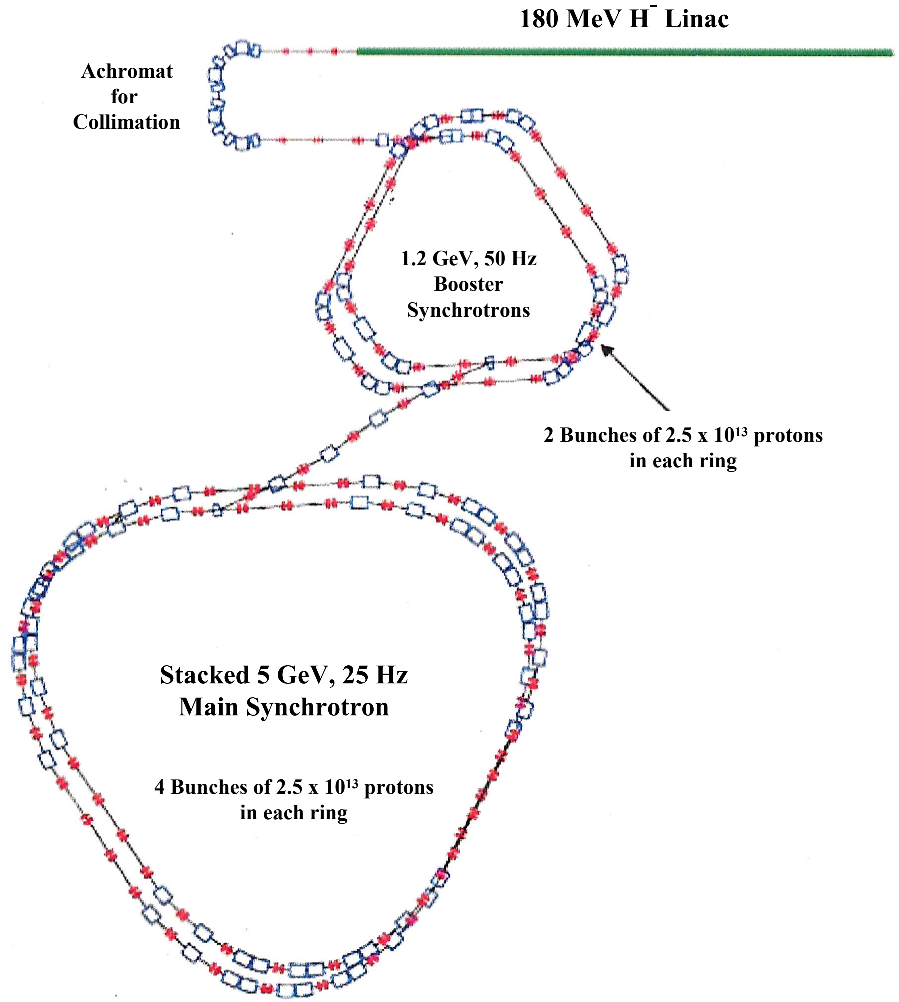
RAL proton driver proposal

5 GeV, 0.8 mA , 4 MW, 50 Hz

After Main Synchrotrons: DF: ~ 8 x 10^{-7}, I_{peak} ~ 1 kA

Bunch compression using transition energy

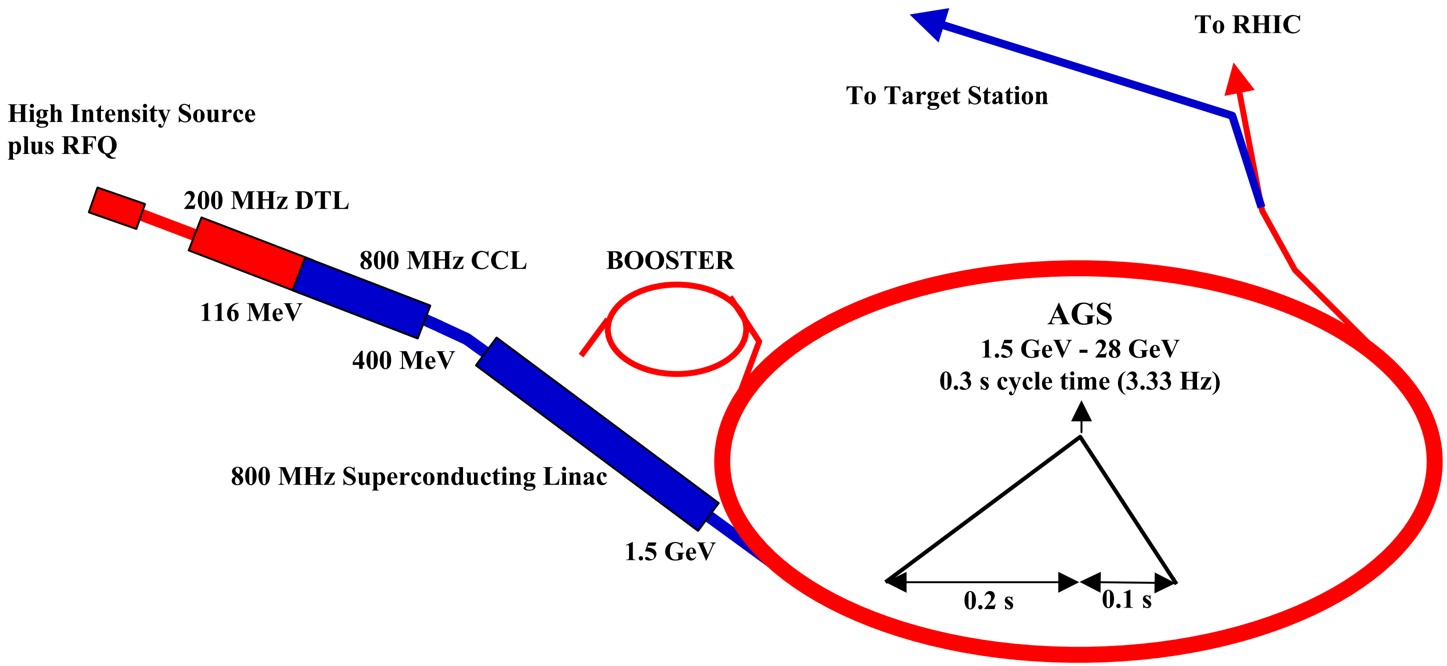


BNL AGS Upgrade to 2 MW

28 GeV, 0.07 mA , 2 MW, 3.33 Hz

After AGS: DF: ~ 4 x 10^{-6}, I_{peak} ~ 16 A

1.5 GeV superconducting linac extension for direct injection of ~ 1.4 × 10^{14} protons



FFAG proton drivers

Renewed interest in Fixed Field Alternate Gradient (FFAG) accelerators

Advantages: High repetition rate (~ kHz), final energy > 1 GeV

Successful demonstration of scaling (fixed tune) FFAG

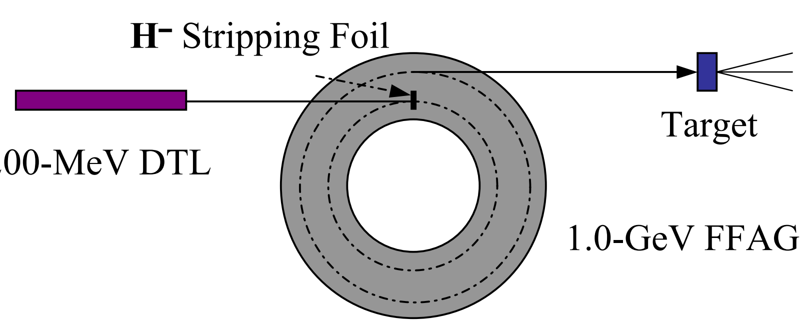
Non-scaling designs with small tune variation are being developed

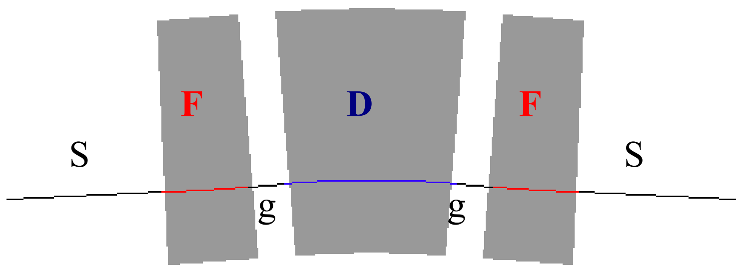
Example: Idea of a 10 MW proton driver (A. G. Ruggiero):

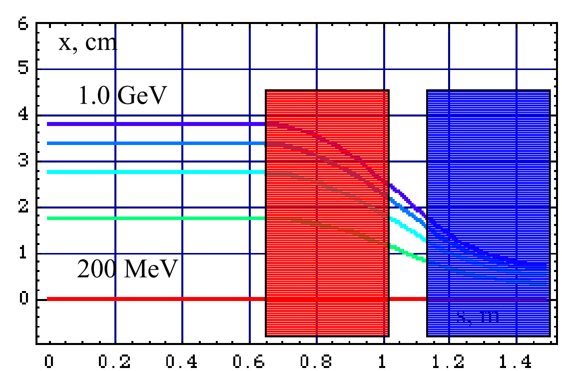
1 GeV, 10 mA , 10 MW, 1 kHz

After FFAG: DF: ~ 3 x 10^{-4}, I_{peak} ~ 30 A

Issues: High rf power, fast frequency tuning,
complicated magnetic field profile







Conclusions

Multi-MW facilities are being planned with DF from CW to 10^{-6}

Designs for a CW facility with 10 MW beam power are mature. Construction of such a facility should be the next step of the development of high intensity proton accelerators. (SCL can go to even higher power)

Several excellent and detailed designs for Multi-MW low DF facilities exist. The designs will benefit from the experience with projects presently under construction (SNS, J-PARC).